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Dish Stirling advanced latent storage feasibility

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Abstract

Dish-Stirling systems have been demonstrated to provide high-efficiency solar-only electrical generation, holding the world record at 31.25%. This high efficiency results in a system with a high possibility of meeting the DOE SunShot goal of \$0.06/kWh. Current dish-Stirling systems do not incorporate thermal storage. For the next generation of non-intermittent and cost-competitive solar power plants, we propose a thermal energy storage system that combines latent (phase-change) energy transport and latent energy storage in order to match the isothermal input requirements of Stirling engines while also maximizing the exergetic efficiency of the entire system.

This paper reports on the technical advantages and challenges of dish Stirling with storage, to make a preliminary estimate as to the technical feasibility of such a system. The proposed system with storage incorporates high temperature latent transport and latent storage, providing an exergetic match to the isothermal input of the Stirling cycle. The transport from the receiver to the storage, and from storage to the engine, is accomplished with advanced sodium heat pipes. The storage is in a solid-liquid phase change material (PCM), likely a metallic eutectic to reduce exergy losses in thermal conduction.

We model a dish Stirling system at a block level, using a combination of real data from several dish systems with and without heat pipe transport, and determine annual energy production and revenue streams based on Barstow California weather data and Southern California Edison Time of Day pricing. We optimize the system on solar multiple, capacity of storage, and several operational strategies.

We find that a storage system using metallic eutectic phase change storage results in a feasible physical embodiment, with mass, volume, and complexity suitable for 25kW_e dish Stirling systems. The results indicate a system with 6 hours of storage and a solar multiple of 1.25 provides the optimum impact to LCOE and profit for the range of cases studied.

A storage system applied to dish Stirling will leverage the current high performance systems, increasing the value to the utilities and transmission entities. A feasible embodiment has been proposed, which with sufficient development will re-establish dish Stirling as a leading energy option.

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1. Dish storage background

1.1. Dish Stirling system configurations

Dish engine systems are point-focus “distributed” systems, typically sized for 3 to 30 kW of electrical output. Some industry partners have determined that large single-site deployments of dish systems can lead to utility-scale implementations with a cost-effective deployment [1, 2]. The dish systems are two-axis tracking, point focus systems with geometric concentration ratios (at the aperture) of typically 3000:1.

Typical dish systems are a “balanced” system with a pedestal drive, Figure 1a. The pedestal drive system allows the loads to be brought to a central location. The engine package is typically quite heavy, and extended on a boom in front of the dish. In order to reduce drive loads, the system is nearly balanced at the elevation pivot, which is in front of the dish surface. This in turn requires a “slot” in the dish reflective surface to accommodate the drive support pedestal. This slot reduces the strength of the dish structure. Most current typical dishes consist of a steel back structure, with independent facets mounted to the steel frame and adjusted to “align” the dish.

1.2. Stirling technology

The engine of choice for dish-engine systems is the Stirling Cycle engine. The ideal Stirling cycle has an area equivalent to the Carnot cycle on the temperature-Entropy diagram (T-S diagram), and thus can approach the ideal system performance more than other practical thermodynamic cycles. The Stirling Cycle features isothermal input (3-4 on Figure 1b), unlike Brayton or Rankine cycles which require sensible heating at the input. Practical Stirling cycle engines are available with input temperatures approaching 800°C.

Dish-Stirling solar systems have been demonstrated to provide high efficiency solar-only electricity generation, holding the world record at 31.25% net conversion from sunlight to 3-phase grid power. This high efficiency results in a system with a high possibility of meeting the DOE SunShot goal of \$0.06/kWh. Current dish-Stirling systems do not incorporate thermal storage, but operate only when the sun is shining. The receiver of the Stirling cycle is typically a bundle of tubes through which the engine working fluid, hydrogen or helium, shuttles back and forth. The engine has little thermal inertia, with a cold startup to full power completed in several minutes rather than hours. Conversely, upon loss of solar input (clouds or sunset), the output is diminished rapidly.

In large installations, dish-to-dish shading is important. A Sandia National Laboratories study [3] indicated that the Stirling Energy Systems (SES) 25kW_e system could operate to about 10.5% shading, after which unbalanced cylinder operation caused a controls trip on the engine. In a large field, shading in the morning, evening, and noon near the Winter solstice resulted in a loss of 5-6% of the generation compared to a standalone system. A heat pipe receiver could increase the allowable shading fraction, and therefore increase the annual energy capture of the system.

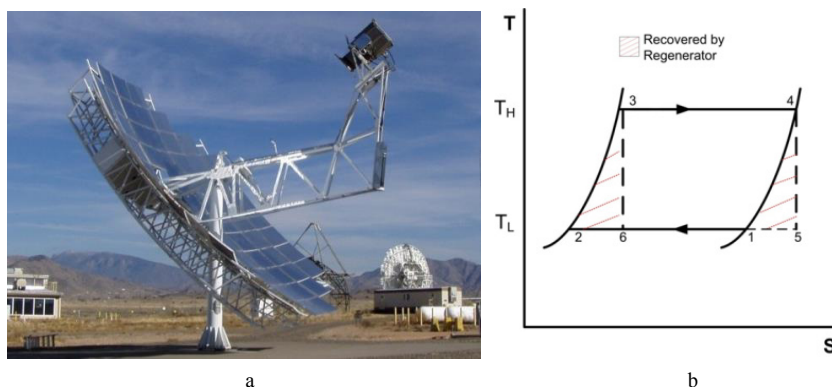


Figure 1. a) McDonnell Douglas dish, showing typical balanced configuration. b) . Temperature-Entropy diagram comparing the Ideal Stirling Cycle (1,2,3,4) and Ideal Carnot Cycle(5,6,3,4).

However, the same study indicates that dish-Stirling takes good advantage of the lucrative summer afternoon bonus offered by Southern California Edison (SCE) and other utilities in their rate structure. The current rate structures put little premium on the evening hours, and the Solar-only Stirling systems operated through much of the peak value hours. Other California utilities have similar Time of Delivery (TOD) rate structures, though none favor the afternoon as strongly as SCE. None of the TOD schedules give significant emphasis to evening generation.

SES indicated that they planned to install systems in large fields at \$2-3/W [1], and the 25kWe rated system would generate about 56MW-hr/year. With a fixed charge rate of 7.42% [4] and O&M at \$0.045/W/year, the projected LCOE is \$0.085/kWh. Using the current SCE TOD rate structure (Table 1) [5] and a base price of \$0.10/kWh, the effective value of the system (value of the energy generated, averaged over the year) is \$0.14/kWh.

The dish Stirling systems, as presented by SES [6], have the potential for reaching SunShot goals (\$0.06/kWh) with supply chain development, design for manufacture, and offshore sourcing, without any difficult technical challenges. Onshore manufacture was anticipated to add about \$0.02/kWh.

This paper will explore the feasibility of adding storage to the SES-sized dish Stirling systems. The results of this paper can guide next-generation development to provide a system that not only matches the DOE SunShot projected price performance, but also incorporates significant thermal storage to ride through transients and extend capacity.

Table 1. Southern Cal Edison TOD multiplier factors from 2011

Season	Period	Definition	Factor
Summer June 1 - September 30	On-Peak	WDxH ¹ , noon-6 pm	3.13
	Mid-Peak	WDxH, 8-noon, 6-11 pm	1.35
	Off-Peak	All other times	0.75
Winter October 1 - May 31	Mid-Peak	WDxH, 8 am-9 pm	1.00
	Off-Peak	WDxH, 6-8 am, 9 pm-midnight; WE/H ² 6 am-midnight	0.83
	Super-Off-Peak	Midnight-6 am	0.61

1/ WDxH is defined as weekdays except holidays

2/ WE/H is defined as weekends and holidays

1.3. Proposed storage configuration

For the next generation of non-intermittent and cost-competitive solar power plants, we propose a thermal energy storage system that combines latent-energy transport and latent-energy storage in order to maximize the exergetic efficiency of the entire system, matching the isothermal input of the Stirling cycle engine. We propose a configuration that allows implementation on the movable portion of the dish—eliminating the need for high-temperature rotating or flexible joints and minimizing heat losses in thermal transport. In addition, we propose using Sandia-developed high-performance heat pipes that allow extension of storage to large (25 kWe) systems. This configuration was originally proposed as an ARPae HEATS project [7] and detailed in a Sandia report [8].

Our proposed configuration centers on providing transport that enables storage and engine mounting on the rear of the dish rather than at the focus. This allows a substantially higher thermal storage mass than can be supported on the power conversion unit (PCU) cantilever boom, facilitating storage durations of six or more hours. Figure 2 schematically shows the proposed system layout (not to scale: The dish is typically 11-12m in diameter. The proposed storage media is approximately 1m³). A pumped condensate heat pipe transports energy from the solar receiver to the storage media nearly isothermally. The storage media is a salt or metallic Phase Change Material (PCM), for high-density isothermal storage. A second isothermal heat pipe transports the thermal energy from storage to the engine, providing high flux to the engine through condensation. The separate heat pipe systems provide a “thermal diode” effect to reduce thermal losses when operating from stored energy.

The proposed approach leverages the existing high-temperature (700–800°C), high efficiency dish Stirling system, and provides a storage option. In contrast, in order to approach SunShot goals, trough and tower high-temperature storage systems need further development to provide a high-temperature thermodynamic cycle and receiver, as well as high-concentration optics suitable to limit collection losses.

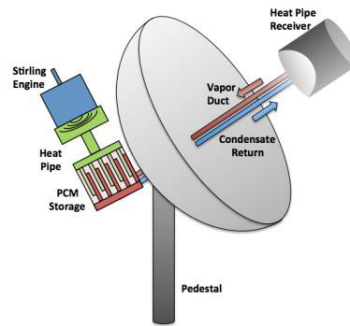


Figure 2. Schematic of proposed latent energy storage system for dish-Stirling power generation

The development work includes developing and demonstrating high-performance interfaces throughout the proposed system. A successful system design includes proving and characterizing these interfaces. The first interface is the solar-to-heat pipe (receiver), which requires a high performance robust wick system to properly distribute the heat transport fluid to the receiver. The second interface is the heat-pipe-condenser-to-storage-media. This interface requires a thorough understanding of the dynamic heat-transfer characteristics at various stages of PCM melt. The third interface is similar to the second, involving the energy transport out of storage and into the secondary heat pipe vapor space. Finally, we must consider the interface with the engine, which is highly design-specific. For test purposes we will simulate this with gas-gap calorimeters to characterize heat transfer rates.

Sandia is a recognized leader in dish-Stirling technology development. Sandia developed very high performance heat-pipe receivers in the 1990s and demonstrated operation with a Stirling system on sun[9]. Sandia has also performed as the lead lab on thermal storage technologies for CSP and has expertise in storage media formulation, for both sensible and latent storage systems. Being one of the nation's lead weapons laboratories, Sandia also has key expertise in long-term materials compatibility, a key concern for storage systems. We can leverage expertise throughout Sandia to support this project as needed.

The proposed system takes the highest performance solar electric generation system and moves it to the realm of intermediate, non-intermittent power generation. This expands the capability of the systems with the best chance of meeting the aggressive SunShot leveled cost of energy (LCOE) goals, without needing complimentary programs to develop other high-temperature, high-performance subsystems.

2. Systems study

A simplified systems model was developed to explore appropriate sizing and operation of a dish-Stirling storage system, and to evaluate at a high level the impacts on LCOE. The model is intended to explore trends and overall impact, but would need further refinement to be used as a design tool. The systems level model is used to determine the overall feasibility, defined as impact on the LCOE of the system, of a latent heat storage system for dish Stirling. Further, the model provides high-level insights into the sizing requirements. For the heat pipe receiver (solar interface) sizing, too large a required solar multiple could place the system beyond near-term feasibility.

The model is based on a previous systems model [3], which considers a full field of dish systems, including shading dish to dish. The original model was based on the SES MPP-vintage dish (rectangular facets, "Model Power Plant"), and used measured data to develop the linear operation curve. The model uses 1977 Solergy data (15-minute data) from ground-based measurements in Barstow CA. The model was modified to support operation with storage. A thermal accumulator was added, with a user-specified capacity per dish. Each dish accumulator was tracked separately, due to edge effects in the field.

The thermal performance of the system was separated from the system performance, based on prior dish Stirling system modeling results [10]. These prior modeling efforts separated the engine performance from the system performance based on thermal modeling of the Direct Illumination Receiver (DIR). Other prior work [9] indicated

that the heat pipe receiver has about 93% thermal efficiency at rated power, while the DIR rated efficiency is only 85%, primarily due to the uncooled ceramic stone in the center of the receiver, which has a large view factor to the environment. In addition, the same prior experimental work indicates that the system performance is enhanced by about 3kW_e output, from about 18kW_e with a DIR and hydrogen working fluid to 21kW_e with a heat pipe receiver and helium working fluid. The modeled thermal performance combined with the measured system performance, led to thermal and system performance characteristic curves. The intercepted thermal power required to operate the engine at rated power of 25kW_e is reduced from 68.88kW_t to 66.65kW_t by the use of the heat pipe input.

From these characteristic operating curves, the thermal power absorbed by the heat pipe receiver at any given insolation level can be derived, and is applied to the accumulator after accounting for shading effects of surrounding dishes. The system was allowed to operate through 85% shading. Fixed losses, such as re-radiation from the receiver cavity, are accounted for and result in a non-zero minimum breakeven insolation level, below which collection of energy is stopped. A 2kW constant thermal loss from the PCM storage was applied whenever the storage accumulator contained positive energy.

While many controls approaches may be considered, for this study I applied the following controls:

- Engine will not start without 10% storage accumulation
- Engine starts at 12 noon and runs until storage is depleted
- Engine starts early if 80% of storage accumulated prior to noon
- Engine runs at design conditions (25kW_e, 66.65kW_t) at all times
- Solar energy is shed when storage is full (100% melted)
- Only latent storage is considered (no attempt to recover or account for sensible)

Several parameters affect the storage system. The storage capacity is selected in hours of storage assuming full power operation of the engine during storage drawdown. The solar multiple is specified as simply a size scaling of the dish reflecting area, with a solar multiple of 1.0 equal to the original SES MPP-vintage dish. Since the heat-pipe-driven system is more efficient, a solar multiple of 1.0 produces more power than the non-storage system. It is assumed that the field size (dish spacing) will increase proportional to dish linear size, and therefore the shading as a percentage is still valid based on shading in the nominal field size.

Finally, a very simplistic financial model was included. The TOD “value” of the energy produced was calculated on the Southern Cal Edison (SCE) 2011 TOD periods outlined in Resolution E-4442 of the PUC of California, adopted December 1, 2011[5], which provides the market price referent for California. The TOD table indicates multiplier factors for delivery at various times, which modify the base value of the electricity, which was set to \$0.10/kW-hr, consistent with the market price referent for long-term (20-year) contracts in 2015. I did not escalate the payments, but rather modeled a single year of operation. I did not account for weekends or holidays, which currently have an alternative schedule. Table 1 shows the TOD multipliers for SCE for 2011.

A simplistic Levelized Cost of Energy (LCOE) is developed from the approach used by Sargent Lundy [4]. Equation 1 shows the calculation of LCOE for a simple system:

$$LCOE = \frac{(CC*FCR + OM_y) * RatedPower}{AE} \quad (1)$$

Where:

LCOE=Levelized Cost of Energy, \$/kW-hr

CC = Capital Cost, \$/W, set to \$2/W

FCR = Fixed Charge Rate, set to 7.42%

OM_y = O&M costs in \$/W/yr, set to \$0.045/W/yr

Rated Power = Entire plant size in W, set to 500MW

AE = Annual Energy produced in kW-h, as calculated

The Capital costs were based on SES projections of their capital costs [1]. When storage was added to the system, the Capital Cost (CC) was modified to account for the cost of the storage system, in terms of the storage size (includes storage media and interface, both scale with size), a fixed charge for storage (includes the receiver, the vapor duct, the engine interface, and the sodium pump), and the solar multiple (scales the cost of the reflector system, including land, wiring, and other BOP aspects that scale with dish size. The modified CC calculation is then:

$$CCWS = \frac{(SFC + SVC * SC)}{RPPD} + CC * (1 - SF + SF * SM^{1.5}) \quad (2)$$

Where:

CCWS = Capital Cost With Storage, \$/W

SFC = Storage Fixed Cost, \$/dish, set to \$3000/dish

SVC = Storage Variable Cost, \$/kWh_{th}, set to \$20/ kWh_{th}

SC = Storage Capacity, kWh_{th}, user setting

CC = Basic system Capital Cost, \$/W, set to \$2/W

SF = Scaled fraction of dish, set to 50%

SM = Solar multiple

RPPD = Rated Power Per Dish (W)

The first part of the equation represents the capital costs of the storage system itself. Then the capital cost of the system is modified to account for the larger dish. Only a portion of the system cost is scaled, as the engine, controls, and some other parts do not scale with solar multiple. The exponent of 1.5 on the solar multiple is based on Kolb's analysis of heliostat steel cost scaling with heliostat size [11].

The fixed storage cost per dish, at \$3000, is an estimate of the eventual incremental cost of the system with storage over the cost of the DIR system, and does not vary with the storage capacity. The \$20/kW-hr of storage cost is based on an estimate of metallic PCM such as Aluminum-Silicon, plus the incremental cost of heat exchangers, containment, and insulation that scale with capacity. These numbers can be changed as inputs by the user. In addition to the TOD value of the energy and the LCOE, profit is calculated as the difference between the two values.

3. Results

The model was exercised a number of times, varying the storage capacity, the solar multiple, and the start time of the engine output. The relative system performance is evaluated in terms of LCOE and profit. Secondly, the shed thermal energy (when storage is full) is considered a significant system downgrade. If too much energy is shed, the value of the collection hardware is diminished. If no energy is shed, the storage media is probably oversized for the given solar multiple. Both these extremes of shedding impact the LCOE and profit.

The LCOE shows a clear minimum at a solar multiple of 1.25 (Figure 3a). At low solar multiples, the storage is rarely filled, reducing the effectiveness of the storage investment. At higher solar multiples, the shed energy increases, and therefore the increased cost of the dish is not amortized over a proportionally greater amount of energy generated. The same trend is seen regardless of the storage capacity, represented by the various points at each solar multiple. The greatest impact on profit is solar multiple (Figure 3b). The profit goes down with increasing solar multiple due to the shedding impact on LCOE, but also due to the lower sales value of the energy in the night hours. Collecting energy in the lucrative summer afternoon hours, but deferring electrical generation to the night hours has a negative impact on profit due to the TOD rate structure. Both the LCOE and the profit show little response to the hours of storage. Increasing storage capacity allows amortization of the system cost over more energy generated, but the system cost increases as well. As solar multiple increases with a given amount of storage, more energy is shed (Figure 4), limiting the effect of the additional investment. While a solar multiple of 1.0 is most profitable, the generation into the evening hours is limited, and the storage is rarely filled. A solar multiple of 1.25 allows significant evening generation, and typically only a few percent of total energy shed, and appears to be a good compromise. It is clear that, for a given solar multiple, there exists an optimal storage capacity, or vice versa.

Figure 5 shows the increase in energy production on an hourly and monthly basis for the selected storage case of 6 hours storage and 1.25 solar multiple, compared with the solar only case. The increase in total power production, due to the solar multiple and to improved efficiency, is clearly visible. From a profit standpoint, the solar-only version does not fully produce in the 5-6pm hour due to dish-to-dish shading starting about 1 hour before sunset, while the storage version fully produces during this lucrative time. In the summer, the engine starts as early as the 10am hour, but production on a monthly basis does not exceed the solar only system until the noon hour.

Based on the limited modeling performed, it does appear that storage can improve the LCOE of a dish-Stirling system, despite adding to the cost of the system. This is because of several impacts:

- The receiver and engine performance are enhanced by the heat pipe receiver and heat pipe transfer to the engine, as demonstrated in earlier non-storage heat pipe work.

- The engine runs at rated power whenever it does run, which improves the overall annual efficiency. The engine is never run above the rated power, an important life consideration not considered in this LCOE calculation.
- The engine runs at full power during most of the summer afternoon peak, shifting some morning collection into the lucrative afternoon generation period. The non-storage system ceases to generate prior to 6pm standard time due to dish-to-dish shading.
- The storage system allows amortization of fixed system costs over a greater amount of annual energy generation

The storage system can cost as much as \$82/kWh_{th} without negative impact on the LCOE, or \$33k/dish over the solar-only option. The impact on profit, determined by the TOD factors of SCE, is greater than the impact on LCOE.

It appears that the solar multiple does not have to be large, and in fact too high a solar multiple relative to the storage capacity leads to excessive thermal energy shedding when storage is full, reducing the efficacy of the expensive collector system. A solar multiple of 1.25 is sufficient to fill the 6-hour storage on most days, and limits shedding to under 5% of the total energy. This sets the dish size on the order of 100 m², and the heat pipe receiver thermal input at about 94kW, which is within the realm of possible solutions with a Sandia high performance wick structure [12, 13].

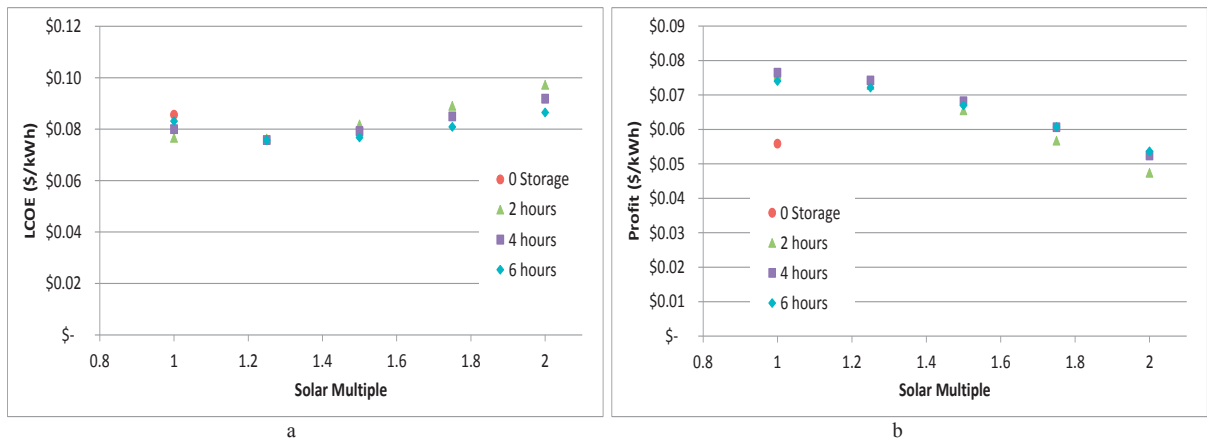


Figure 3. a) Impact of solar multiple on the LCOE. The red diamond is the non-storage DIR system. The different points at each solar multiple are for different storage capacities. b) Impact of solar multiple on plant profit. Profit is the difference between the utility payment (based on a \$0.10/kWh baseline) and the LCOE. The multiple points at each SM are for different storage capacities and start times

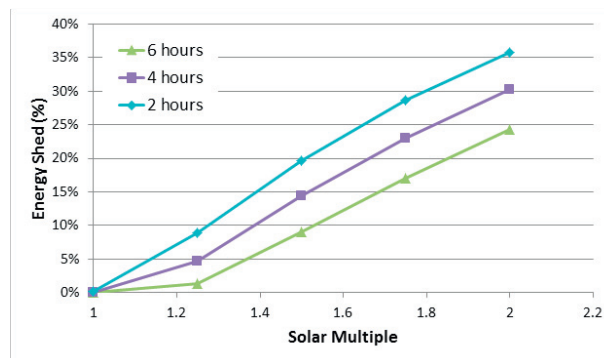


Figure 4. Thermal energy shed from storage due to storage capacity full while on sun, at different solar multiples and capacities (time of capacity).

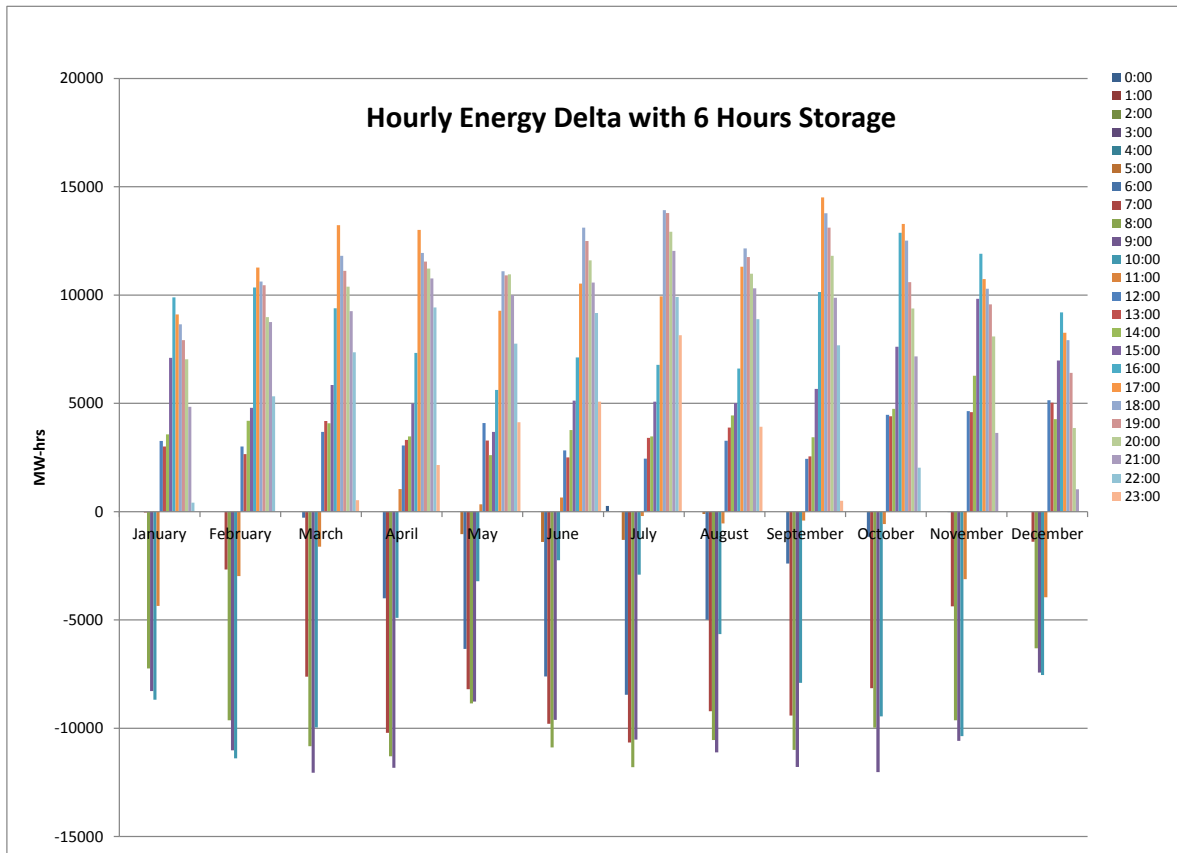


Figure 5. Change in energy produced by adding storage, compared with the no-storage case. In the mornings, little energy is produced by the storage system due to the controls scheme. There is substantially more energy generated in the lucrative summer early evening, especially as shading reduces power about an hour before sunset. This has strong influences on the system annual profit.

The duration of storage required for optimum performance from a profit standpoint will depend upon the TOD revenue. With current TOD tables, the evening hours are not as highly valued as daytime hours, and therefore the optimal size of storage may be driven smaller. If we assume the PUC's and utilities will put further value on evening generation, then it appears that 6 hours of storage, the highest level considered, should be pursued. This allows summer operation on most days past 11pm. As evening value is increased, the optimum hours of storage may also increase. However, it is unlikely that more than 6 hours of storage on a dish system will be technically desirable, due to mass and size of the storage system and the throughput requirements of the receiver heat pipe wick with higher solar multiple.

Higher solar multiples and higher storage capacities do not help on days in which little to no energy is collected. It is not economically feasible to size the system for multiple days of sunless operation, when the vast majority of the days can generate energy in the currently considered configurations. As with all solar systems with storage, high capacity cannot be practically guaranteed, and some backup, either on site or on the grid, must be used for cloudy days and extended outages. Sufficient storage to cover extended cloudy spells is not feasible, as the utilization of the extended capacity, and utilization of the increased capital cost, will be minimal.

Alternative controls strategies can be considered, which can extend operation to later hours by foregoing generation, or reducing power output, during the daytime. This may be a reasonable consideration in the winter, if the evening home heating load is significantly electric. However, in the summer, the system usually started generation before noon, triggered by full storage. A larger storage capacity could allow later starts, but may be under-utilized on an annual basis.

The economic details of a particular project, namely the TOD revenue stream and any capacity payments or penalties (not considered here), must be considered when sizing storage and/or the solar multiple. In addition, the PUC or transmission company may impose further requirements on the operating scenario that are not considered here. For example, significant penalties may be imposed for not generating at key times, or not predicting generation accurately in advance. The storage system, even at a fairly small capacity, can provide a buffer for response times to unexpected poor or transient solar conditions, allowing the utility to bring other reserves on line with sufficient notice, and avoid penalties. The costs and other economic considerations in this high-level look should be considered parametric, rather than representative of a particular installation.

4. PCM storage media

The selection of a Phase Change Material (PCM) appropriate to the temperature range of the Stirling engine is critical to the success of the storage system. The configuration of the storage differs from other CSP storage projects in several ways:

- The input surface temperature of the Stirling engine is 750-800°C
- The thermal input and output to the PCM is by separate heat pipe tubes, thus the heat flow is in one direction
- The gravity vector changes throughout operation

A conduction-only model was used to compare salt PCM's (NaCl) to metallic PCM's (Cu-Si). The spacing and number of heat pipe condensers and evaporators were varied to maintain 45°C temperature drop through the PCM storage system, a figure arrived at to maintain 95% exergetic efficiency [8]. In order to thus limit the temperature drop at full power, the salt version required about 200 tube pairs (200 evaporators and 200 condensers), while the metallic version required fewer than 20 tube pairs. Further detailed modeling [14] has shown that natural convection is unimportant in the metallic case due to high conductivity, and in the salt case due to the need for enhanced surface area (fins) which impede the convection. Further, the melt zone is very organized and linear between tube pairs, since the thermal energy is always input through one tube and extracted through the other.

5. Additional technical concerns

The primary technical development concerns for this implementation have been identified as:

- PCM selection, characterization, and compatibility with cost-effective containment
- Solar receiver heat pipe wick performance, with high peak flux and high total power throughput
- PCM system performance (modeling and bench-scale demonstration)
- Cost and impact on LCOE (systems modeling)

These issues are in the process of being addressed in a DOE-funded program at Sandia National Laboratories. In addition, the following technical issues must be considered, but are seen as engineering issues rather than potential show-stoppers. These issues are best handled by the dish system integrator:

- Heat pipe to engine interface, particularly thermal stress issues
- Liquid metal pump selection or design for solar receiver return flow
- System-wide thermal expansion issues, especially in the long heat pipe receiver and thermal transport system
- Freezing and startup sequencing and sodium inventory management
- Thermo-mechanical ratcheting within the PCM system
- Management of full storage (shedding)
- Thermal loss management (insulation design)
- Safety, with considerable hot liquid metals quantities
- Dish redesign to accommodate the loads and to optimize the structure

6. Conclusions

A first-order systems analysis has shown that a storage system for dish Stirling can add value and lower LCOE. Within the range of parameters considered, the optimum storage capacity is 6 hours, with a solar multiple of 1.25, resulting in a near-term physically feasible embodiment in terms of receiver power throughput and mass of the system. The storage system allowable cost, set by no negative impact on LCOE compared to solar-only, is up to \$82/kWh_{th}, driven by the high efficiency performance of the dish Stirling approach. This value opens the possibility of incorporating more expensive metallic PCM's in order to optimize exergetic performance.

A simple conduction model indicates that the option of metallic PCM provides a solution space with a feasible number of heat pipe tubes within the PCM containment. A salt-based PCM system suffers from low conductivity and requires a very large a number of tubes, which is likely cost-prohibitive. Several metallic PCM's are under investigation for thermal properties and materials compatibility.

The proposed embodiment places the heavy storage and engine on the back of the dish, eliminating rotating or flexible joints in the thermal transport system, and potentially improving the dish structural design. However, this embodiment requires the development of a large latent transport system and demonstration of high power heat pipe capabilities.

Immediate technical development is needed in the areas of PCM identification, characterization, compatibility, and cost reduction. The high power heat pipe must be developed and demonstrated. The entire system concept must be demonstrated in hardware and models in order to confirm the simplifying assumptions in the systems model. A number of engineering issues must be addressed by the systems integrator after basic feasibility is demonstrated.

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